

CURRENT CONTROL METHOD AND APPARATUS FOR ACTIVE POWER FILTERS

Background of the Invention

5 1. *Field of the Invention*

The present invention relates to power filters in general, and to active power filters in particular.

2. *Description of the Prior Art*

10 The wide use of nonlinear loads has increased the harmonic content of the voltage and current waveforms in alternating current (AC) power distribution systems. In many cases large numbers of such loads are operating, causing a corresponding increase in power line harmonics. Such harmonic currents in conjunction with their associated source impedances produce distortion of the line voltages which can cause
15 equipment to malfunction.

To address the above problems, active power filters (APF) have been used for compensation of polluting harmonics on electricity distribution networks. An APF is a device that is connected to a power line and cancels the reactive and harmonic currents
20 from a group of nonlinear loads so that the resulting total current drawn from an AC source is sinusoidal. Ideally, the APF needs to generate just enough reactive and harmonic current to compensate the nonlinear loads on the line, thus it handles only a fraction of the total power to the loads.

In one conventional APF design, an open loop scheme is used to control the APF current, as generally described by E. Dallago and M. Passoni in an article titled "Single-Phase Active Power Filter with Only Line Current Sensing", IEEE Electronics Letters, 5 20th January 2000, Vol. 36, No. 2, pp. 105-106, and by K. M. Smedley, L. Zhou, and C. Qiao in an article titled "Unified Constant Frequency Control of Active Power Filters- Steady State and Dynamics", IEEE Transactions on Power Electronics, Vol.16, No. 3, May 2001, pp. 428-436. In these systems the APF is controlled such that the output voltage of the APF is proportional to the input source current. This causes the 10 impedance seen by the power source to appear resistive, hence maintaining the input current approximately proportional to the input voltage.

In another conventional APF design, a closed input current loop with a reference multiplier is used, as described by F. P. de Souza and I. Barbi in an article titled "Single- 15 Phase Active Power Filters for Distributed Power Factor Correction", IEEE PESC 2000, pp. 500-505. A current loop is used to force the input source current to track the input source voltage, thereby achieving near-unity power factor.

However, in the above approaches, only the input source current is measured. 20 This makes it difficult to control the current flow from the APF and the load. Hence, if there is an overload condition at the load, the APF control will attempt to deliver the current demanded, even if the demand is beyond the design limits of the APF.

There is, therefore, a need for an APF control method and apparatus that limit the APF current, and allow transition from a normal condition to an overload condition and back again in stable manner, while maintaining the lowest input current distortion within the design limits of the APF.

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Brief Summary of the Invention

The present invention addresses the above needs. In one embodiment the present invention provides an active filtering method and apparatus for controlling a current generator that generates an APF current for compensating polluting harmonics on a power line that connects a power source and a load. A feedback loop regulates the APF current by sensing the current output of the current generator and the current flowing through the load. The feedback loop controls the current generator to force the APF current to track a current command signal to provide near unity power factor (i.e., proportional current), while effectively limiting the APF current to a safe value within the limitations of a particular design.

In one implementation, an active filter is provided that can be connected to a power line between a power source and a load. The active filter comprises a current generator that in response to a control signal generates an APF current to compensate for polluting harmonics on the power line. The active filter further includes a controller that controls the current generator to compensate for the polluting harmonics on the power line, such that the APF current does not exceed a selected threshold value.

Preferably, the controller further includes a limiter that generates said control signal based on feedback values of the APF current and the load current, to control the current generator such that the APF current does not exceed the selected threshold value. In one example, the active filter can include a first sensor that senses the APF
5 current and provides a corresponding signal to the limiter that represents the feedback value for the APF current, and a second sensor that senses the load current and provides a corresponding signal to the limiter that represents the feedback value for the load current.

10 As such, the limiter is configured to control the current generator such that even if the APF current necessary to compensate for the polluting harmonics on the power line exceeds said selected threshold value, the APF current generated by the current generator is limited to at most the selected threshold value. The present invention provides overload protection of the APF, low input current distortion, and stable
15 operation of the APF into and out of overload conditions while maintaining minimum input current distortion within the bounds of the APF design limits.

While the apparatus and method has or will be described for the sake of grammatical fluidity with functional explanations, it is to be expressly understood that
20 the claims, unless expressly formulated under 35 USC 112, are not to be construed as necessarily limited in any way by the construction of “means” or “steps” limitations, but are to be accorded the full scope of the meaning and equivalents of the definition provided by the claims under the judicial doctrine of equivalents, and in the case where

the claims are expressly formulated under 35 USC 112 are to be accorded full statutory equivalents under 35 USC 112. The invention can be better visualized by turning now to the following drawings wherein like elements are referenced by like numerals.

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Brief Description of the Drawings

FIG. 1 is an example block diagram of an embodiment of an active power filter (APF) according to the present invention, interconnected in a parallel circuit with a load and a power source;

10 FIG. 2 is an example detailed functional block diagram of an embodiment of the active power filter of FIG. 1, interconnected in a parallel circuit with a load and a power source; and

FIG. 3 is an example functional block diagram of an example implementation of the active power filter of FIG. 2, interconnected in a parallel circuit with a load and a power source.

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The invention and its various embodiments can now be better understood by turning to the following detailed description of the preferred embodiments which are presented as illustrated examples of the invention defined in the claims. It is expressly understood that the invention as defined by the claims may be broader than the

20 illustrated embodiments described below.

Detailed Description of the Preferred Embodiments

Referring to **FIG. 1**, an example block diagram of an embodiment of an APF apparatus 10 according to the present invention is shown, interconnected in parallel in a circuit 12 that includes a load 14 having an impedance Z_L and a voltage source 16 providing a voltage v_S . The APF 10 generates (i.e., sources or sinks) the current i_{APF} as necessary to compensate for the polluting harmonics on the power line 11 in the circuit 12.

The APF 10 includes a limiter 18 to control and limit the APF current i_{APF} to a desirable/safe threshold value. To do so, the APF current i_{APF} and the load current i_L are measured using two sensors 20, 22, respectively, and the sensed values are used by the limiter 18 to control the APF current i_{APF} directly.

The APF 10 operates in the circuit 12 such that:

$$i_{APF} = i_L - i_S \quad (1)$$

The desired (ideal) input source current i_S is proportional to the input voltage v_S in order to achieve unity input power factor, such that:

$$i_S = v_S / R_{EM} \quad (2)$$

wherein R_{EM} is the emulation resistance, or the equivalent resistance seen by the input voltage source v_S .

To achieve the above desired performance, the APF current i_{APF} is controlled so that:

$$i_{APF} = i_L - v_S / R_{EM} \quad (3)$$

If, however, the required APF current (to essentially cancel out said harmonics) exceeds a design limit I_{max} , then the APF current i_{APF} is limited by the limiter 18 to the selected threshold value I_{max} according to the following relation:

$$i_{APF} = \begin{cases} i_L - v_S / R_{EM} ; & |i_L - v_S / R_{EM}| < I_{max} \\ I_{max} ; & |i_L - v_S / R_{EM}| \geq I_{max} \end{cases} \quad (4)$$

To accomplish this control strategy, a first (inner) control loop is closed around the APF current i_{APF} . **FIG. 2** shows an example functional block diagram of an embodiment of the APF 10 according to the present invention, which includes the inner control loop, wherein the APF 10 is shown interconnected in parallel in the circuit 12 including the load 14 and the voltage source 16.

In this example, the APF 10 includes an APF current generator 24, an APF current controller 26 and a reference current generator 28. The inner control loop is formed via the APF current controller 26 and the APF current generator 24, wherein the APF current generator 24 sources or sinks the current i_{APF} as controlled by the APF current controller 26.

The limiter 18 in the APF current controller 26 provides APF current control based on the measured/feedback values of the currents i_{APF} and i_L . As such, the APF current controller 26 never commands more current than the APF current generator 18 is capable of delivering safely.

The APF current generator 24 includes an energy storage device (e.g., capacitor, inductor, etc.) that sinks or sources current as needed to compensate for said polluting harmonics. A second (outer) control loop in the APF 10 maintains the energy level (e.g., capacitor voltage, inductor current, etc.) of the energy storage device at a safe value. The outer control loop is formed via the reference current generator 28 with the APF current generator 24 feeding back the energy level of the energy storage device into the reference current generator 28.

In the example described below, wherein the energy storage device comprises a capacitor, the reference current generator 28 determines the value of R_{EM} based on the energy storage device voltage, and generates the value v_S / R_{EM} for the APF current controller 26. As such, the outer control loop determines the value of R_{EM} that provides an energy balance such that the energy storage source voltage does not grow too large (i.e., the outer control loop provides the proper value of R_{EM} for scaling V_S in relation 4 above).

FIG. 3 is a functional block diagram illustrating an example implementation of the APF 10 of FIG. 2, according to an embodiment of the present invention. The APF current generator 24, the APF current controller 26 and the reference current generator 28 are shown connected in a parallel circuit with the load 14 and the voltage source 16.

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In this embodiment, the APF current generator 24 includes an H-bridge that can source or sink current through an inductor. In this example, the H-bridge comprises four controllable switches 30 (e.g., IGBT, MOSFET, etc.) connected in an H pattern. The switches 30 can be controlled by the APF current controller 26 to allow sourcing or
10 sinking current from/to said energy storage device, such as a capacitor 32, through an inductor 34.

The APF current controller 26 includes a first summer 36, the limiter 18, a second summer 38, a gain amplifier 40 and a modulator 42. A current command signal i_{cmd} is
15 generated at the output of the summer 36 using the input values i_L from the current sensor 22 and V_S / R_{EM} from the reference current generator 28, wherein:

$$i_{cmd} = i_L - v_S / R_{EM} \quad (5)$$

The current command signal i_{cmd} is then bounded by the limiter 18. The limiter
20 output is a bounded current command signal i_{cmd}^* , which serves as the reference current

for the inner current loop. In this example, the bounded current command signal i_{cmd}^* is generated according to the following relation:

$$i_{cmd}^* = \begin{cases} i_L - v_S / R_{EM} ; & |i_L - v_S / R_{EM}| < I_{max} \\ I_{max} ; & |i_L - v_S / R_{EM}| \geq I_{max} \end{cases} \quad (6)$$

5 The bounded command current i_{cmd}^* and the sensed current i_{APF} are combined in the summer 38 and passed through the gain amplifier 40, to provide input control to the modulator 42. The modulator 42 provides four outputs (A, B, C, D) for the four switches 30 in the APF current generator 24, respectively, wherein each MOSFET switch 30 is given a duty cycle by the action of the modulator 42 for the capacitor 32 to sink or
10 source current while satisfying relations (4)-(6) above.

As such, the wide bandwidth inner control loop is used to control the current generator 24 to force the APF current i_{APF} to track the bounded command current i_{cmd}^* , thereby achieving the desired performance according to relation (6) above. The APF
15 current i_{APF} is sensed directly, while the command current, $i_L - v_S / R_{EM}$, is bounded by the limiter 18.

Accordingly, a current control method according to the present invention combines two major feedback/control loops. The first feedback loop (said inner control
20 loop) regulates the APF current i_{APF} using the two current sensors 20, 22. The first feedback loop forces the APF current to track the bounded current command signal to

provide near unity power factor (i.e., proportional current), while effectively limiting the APF current to a safe value within the limitations of a particular design.

The second feedback loop (said outer control loop) is provided to regulate the high voltage buss. The second feedback loop has a low crossover frequency below that of the input AC line, and includes the reference current generator 28. In this example, the reference current generator 28 comprises a summer 44, a gain amplifier 46 and an analog multiplier 48.

The summer 44 determines the difference between the capacitor voltage v_C in the APF current generator 24 and a reference voltage v_{REF} . The output of the gain amplifier 46 represents an error signal (i.e., indicating the value $1/R_{EM}$) which is fed to the analog multiplier 48. The analog multiplier 48 uses the error signal to scale the input voltage signal V_S and generates the reference signal V_S / R_{EM} .

As noted, the difference between the load current signal i_L and the reference signal V_S / R_{EM} is the current command signal i_{cmd} , wherein the APF performance is ideal to the extent that the APF current i_{APF} tracks the current command signal i_{cmd} .

As such, the present invention provides inherent overload protection for the APF 10, low input current distortion, and stable operation of the APF 10 into and out of overload conditions while maintaining minimum input current distortion within the bounds of the APF design limits. Although in the above examples the load current i_L

was sensed to provide necessary shaping of the input current waveform, either the input source current i_S or preferably the load current i_L can be used.

Further, though in the description and claims herein the APF current generator is
5 described to generate a current i_{APF} , those skilled in the art recognize that generating the current i_{APF} in this context means sourcing or sinking a current as necessary to compensate for the polluting harmonics on the power line in accordance with relations (4)-(6) above.

10 In another aspect of the present invention, the current generator is controlled to compensate for the polluting harmonics on the power line, such that the current i_{APF} is bounded by a selected upper threshold and a selected lower threshold.

Many alterations and modifications may be made by those having ordinary skill in
15 the art without departing from the spirit and scope of the invention. Therefore, it must be understood that the illustrated embodiment has been set forth only for the purposes of example and that it should not be taken as limiting the invention as defined by the following claims. For example, notwithstanding the fact that the elements of a claim are set forth below in a certain combination, it must be expressly understood that the
20 invention includes other combinations of fewer, more or different elements, which are disclosed in above even when not initially claimed in such combinations.

The words used in this specification to describe the invention and its various embodiments are to be understood not only in the sense of their commonly defined meanings, but to include by special definition in this specification structure, material or acts beyond the scope of the commonly defined meanings. Thus if an element can be
5 understood in the context of this specification as including more than one meaning, then its use in a claim must be understood as being generic to all possible meanings supported by the specification and by the word itself.

The definitions of the words or elements of the following claims are, therefore,
10 defined in this specification to include not only the combination of elements which are literally set forth, but all equivalent structure, material or acts for performing substantially the same function in substantially the same way to obtain substantially the same result. In this sense it is therefore contemplated that an equivalent substitution of two or more elements may be made for any one of the elements in the claims below or that a single
15 element may be substituted for two or more elements in a claim. Although elements may be described above as acting in certain combinations and even initially claimed as such, it is to be expressly understood that one or more elements from a claimed combination can in some cases be excised from the combination and that the claimed combination may be directed to a subcombination or variation of a subcombination.

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Insubstantial changes from the claimed subject matter as viewed by a person with ordinary skill in the art, now known or later devised, are expressly contemplated as being equivalently within the scope of the claims. Therefore, obvious substitutions now

or later known to one with ordinary skill in the art are defined to be within the scope of the defined elements.

The claims are thus to be understood to include what is specifically illustrated
5 and described above, what is conceptionally equivalent, what can be obviously substituted and also what essentially incorporates the essential idea of the invention.